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Compressive Fatigue Coaxing in Composites

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Compressive fatigue experiments on unidirectional fiber reinforced composites, of both fiberglass and graphite fiber, reveal that compressive fatigue damage takes place by crack extension directly transverse to the fibers. It is also found that specimens which are first subjected to a few hundred thousand cycles of compressive fatigue at low stress levels, and then subjected to compressive fatigue at high stress levels, will survive longer at high stress levels than specimens which are placed under high compressive fatigue stresses from the outset. The increase of fatigue life at high compressive stress levels can be quite large; increases of fatigue life by as much as a factor of five were observed. The phenomenon of prolonging fatigue life at high stress levels by first "running in" a specimen at low stress levels is called coaxing, and is directly opposite to the often reported cumulative damage phenomena observed in tensile fatigue of composites. A possible mechanism for coaxing in compressive fatigue of composites is offered, and practical applications of the effect are suggested.

Key words: Coaxing; composites; compressive fatigue; fatigue.

1. Introduction

With certain metal alloys it is observed that by fatiguing the alloy first at a low stress level and later at a higher stress level, one may obtain a longer fatigue life at the higher stress level than if one had not first applied the low amplitude fatigue loading [1].[1] In metals the magnitude of this effect, called coaxing, is not large (a 20% increase in fatigue life at high stress is a large coaxing effect), and the mechanisms responsible are not presently understood.

In a study of compressive fatigue of fiber reinforced composites the authors observed very strong coaxing effects (in some cases the fatigue life of the specimen at high stress could be increased by a factor of 5 by first subjecting the specimen to low amplitude fatigue loading). The mechanism of the coaxing effect in fiber reinforced composites appears to derive from differential fatigue cracking rates in the longitudinal and transfibrile directions. This brief paper is offered as a report of the coaxing effects which the authors observed. In addition, certain possible applications of this effect are discussed.

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[1] Figures in brackets indicate literature references at the end of this paper.

2. Fatigue Experiments

A set of experiments in which long flat plates (22.8 × 2.54 × 0.280 cm) of unidirectional fiber reinforced plastics were subjected to pure bending fatigue were carried out. The oscillating bending moment was biased in such a way that the specimen was bent in one direction only. Thus, one side of the specimen was subjected to cyclic tension-release loading while the other side was subjected to cyclic compression-release loading. The specimens were oriented so that the fiber direction was parallel to the principal axis of bending stress in the specimen. In different experiments bending was applied about both the minimum (0.280 cm) and maximum (2.54 cm) cross-sectional dimension of the specimens. A typical specimen is shown in the photograph of figure 1. As indicated in the figure, the ends of the specimens were clamped between aluminum blocks, which were in turn held in the (4 point) bending grips of an SF-IU (Sonntag) fatigue testing machine. This machine applies fatigue loads of fixed amplitude. By proper setting of the static load control of the fatigue machine, the biased moment which gave pure tensile fatigue on one side of the specimen and pure compressive fatigue on the other side, was obtained.

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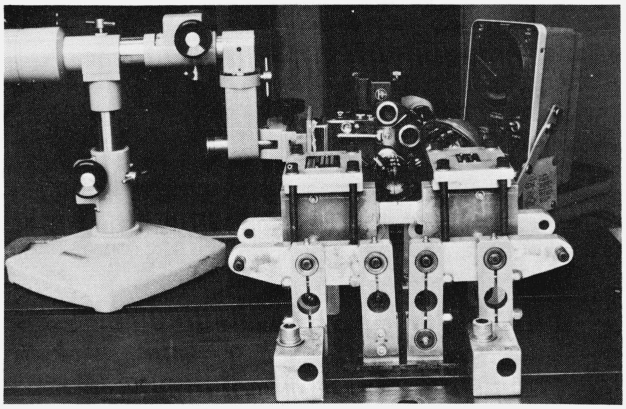

FIGURE 1. *Compressive fatigue experiment in progress.*

3. Materials Studied

Two different materials were studied. Unidirectional fiberglass specimens formed by hot pressing of fiberglass-epoxy pre-preg tape were used.[2] The fiber volume fraction of the final specimens was approximately 60 percent. The tensile strength in the fiber direction was 1.1×10^9 Pa and the elastic modulus in the same direction was 3.26×10^{10} Pa.[3] In addition, specimens of unidirectional graphite fiber reinforced epoxy were formed by hot pressing of pre-preg tape.[4] The final fiber volume fraction of these specimens was approximately 62 percent; the tensile strength of the specimens loaded in the fiber direction was 8.3×10^8 Pa and the elastic modulus in this direction was 1.5×10^{11} Pa.

4. Observations of Experiments

In each specimen fatigue produced fatigue cracking extending directly across the fibers, and originating on the compressive side of the specimen. A more extensive report of compressive fatigue notch extension has been given by the authors elsewhere [2]. In unnotched fiberglass specimens compressive fatigue cracking originated at the points where the aluminum blocks contacted the edges of the specimens. The crack gradually worked its way along the line of contact between the aluminum grip block and the specimen.[5] Several similar specimens were run to failure under different values of nominal compressive stress. Of course, the nominal bending stress gives only an average measure of the intensity of stress in a specimen suffering fatigue. It is used here only as a parameter to indicate the coaxing effect described in this note. (For a treatment of compressive fatigue which takes into account the character of stress at the tip of the propagating notch see ref. 2.) In addition, a collection of specimens was subjected first to fatigue at low stress levels and then to fatigue at high stress levels. Figure 2 shows

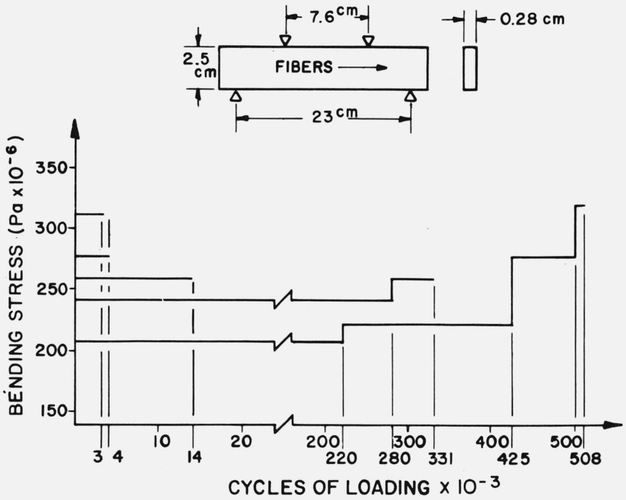

FIGURE 2. *Coaxing of unnotched fiberglass specimens in compressive fatigue (specimens oriented as shown).*

results obtained for a collection of fiberglass specimens. Specimens which were subjected to a nominal bending stress of 314×10^6 Pa fractured, by the compressive fatigue notch extension described above, after only 3×10^3 cycles of loading. At a nominal stress of 272×10^6 Pa the specimen survived only 4×10^3 cycles of loading, and at 255×10^6 Pa the specimen survived only 14×10^3 cycles of loading. However, when a specimen was first subjected to 236×10^6 Pa for 2.8×10^5 cycles (no evidence of fracture was observed) and then raised to 256×10^6 Pa, it survived 5.1×10^4 additional cycles of loading at the higher stress. Similarly, a specimen first subjected to 204×10^6 Pa for 2.2×10^5 cycles of loading, then raised to 216×10^6 Pa for an additional 2.05×10^5 cycles of loading, could then be raised to 272×10^6 Pa for an additional 7.5×10^4 cycles of loading without any evidence of fracture being

[2] The fiberglass pre-preg was supplied by the 3-M Company, and formed and cured according to the manufacturer's specifications. Certain commercial products and instruments are identified in this paper in order to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products or equipment identified are necessarily the best available for the purpose.

[3] The symbol Pa represents the Pascal, the SI unit of stress (1 N/m² or 1.450×10^{-4} lbf/in²). Experimental determinations of strength and modulus were carried out by the authors prior to the fatigue study reported here.

[4] The graphite fiber pre-preg tape was supplied by Whittaker Corp., and consisted of Whittaker Modmor II graphite fiber in B staged 4617 epoxy resin. Forming and curing were carried out according to the manufacturer's recommendations.

[5] While there is nothing surprising in the fact that fatigue damage originated at the contact line between the specimen and the grip, the propagation of a crack directly across the fibers under compression was somewhat unexpected, and the increased fatigue life of specimens subjected to prior fatigue loading was most surprising.

observable, and then raised to 310×10^6 for yet another 8×10^3 cycles of loading before fracture terminated the test.

Fatigue experiments conducted with graphite fiber reinforced specimens also showed coaxing. Figure 3

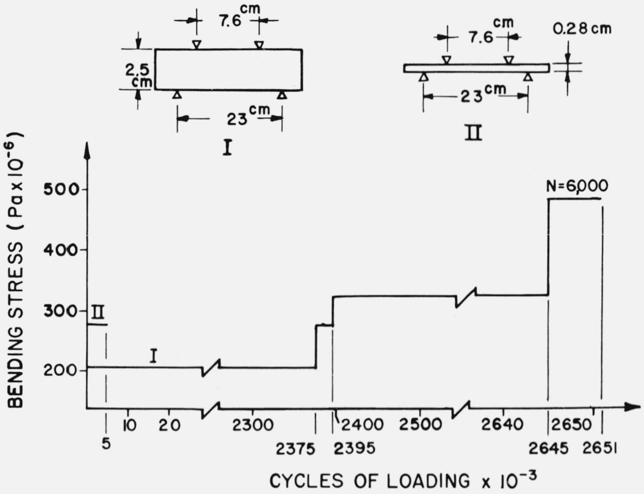

FIGURE 3. *Coaxing of unnotched graphite fiber epoxy specimens in compressive fatigue.*

shows data obtained from pure bending experiments.[6] A nominal compressive stress of 272×10^6 Pa produces a failure of the specimen after 5×10^3 cycles of loading. However, a specimen which is first subjected to 204×10^6 Pa stress for 2.375×10^6 cycles can then be subjected to 275×10^6 Pa for an additional 2.0×10^4 cycles without any evidence of fracture being observable. The specimen can then be subjected to 325×10^6 Pa for 2.5 $\times 10^5$ cycles without observable fatigue damage, and finally can be subjected to 475×10^6 Pa for an additional 6×10^3 cycles of loading before failure of the specimen occurs. The failure of these specimens also occurred by extension of compressive fatigue cracking which originated at the line of contact of the aluminum grip block on the specimen surface.

Finally, prenotched graphite fiber reinforced specimens were studied. The specimens were bent as indicated in figure 4, and were initially notched to depth of 0.254 cm on the side of the specimen subjected to cyclic compression. The notch was cut with a fragment of a diamond impregnated resin, and the notch width at its tip was 7.60×10^{-3} cm; for details of the notch configuration see reference 2. Freshly notched specimens were found to survive a nominal bending stress of 204×10^6 Pa for only 2×10^3 cycles of loading. Compressive fatigue crack extension began immediately upon application of the load; when the crack had progressed approximately two thirds the way across the specimen, tensile fracture occurred on the opposite side of the specimen and terminated the experiment. However, a notched specimen subjected first to a nominal bending stress of 104×10^6 Pa showed no notch extension for 5×10^5 cycles of loading. The specimen was then subjected to 147×10^6 Pa for an additional 10^6 cycles of loading without showing any notch extension, and then to 172×10^6 Pa for yet an additional 2×10^5 cycles without any notch extension occurring. Finally the specimen was subjected to 204×10^6 Pa, and survived for an additional 10^4 cycles of loading before failure. As in the specimens described above, failure occurred via compressive fatigue crack extension from the original notch. Data gathered from experiments with prenotched graphite fiber specimens are shown in figure 4.

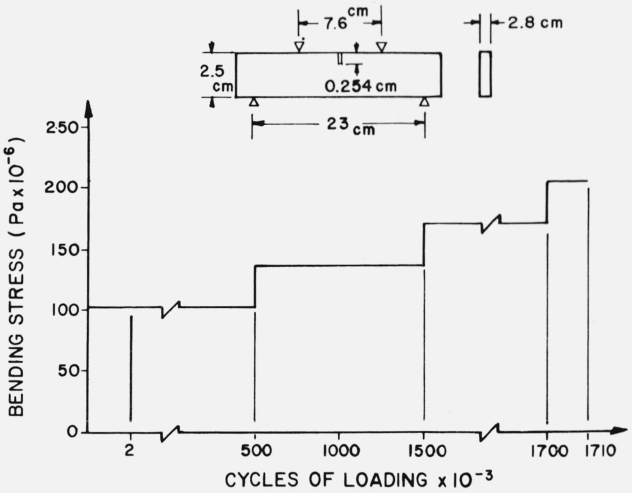

FIGURE 4. *Coaxing of prenotched graphite fiber reinforced epoxy specimens in compressive fatigue.*

5. Summary of Observations

In each of the cases cited above, it was found that initial fatigue loading at a low stress level in some way conditioned the specimen to survive fatigue loading at a high stress level for a greater period than if the low stress fatigue had not been applied. Typically, coaxing extended the fatigue life at high stress level by a factor of 5 (e.g. in fig. 4 a virgin specimen survives 2×10^3 cycles whereas a specimen first subjected to low stress

[6] In the experiments with graphite uncoaxed specimens were bent about the minor axis of the cross section of the specimen and coaxed specimens were bent about the major axis of the cross section, as is indicated in figure 3. This should have no effect on coaxing unless gradients of stress—rather than stress itself—are significant in activating damage. This is viewed as unlikely, but for the sake of completeness the difference in the bending of uncoaxed (II, fig. 3) and coaxed (I, fig. 3) specimens is noted.

fatigue will survive 10^4 cycles; also in fig. 2 similar extensions of high stress fatigue life are seen). The very strong "coaxing" effect seen in the record of compressive fatigue is just the opposite of the cumulative damage phenomena observed in tensile fatigue, and interpreted by (e.g.), Broutman and Sahu [3]. Evidently the mechanisms of compressive fatigue are of different character than those of tensile fatigue.

The mechanism responsible for compressive fatigue crack extension is micro buckling of fibers [2]. The material near the line of contact of the aluminum block on the fiberglass specimens underwent sufficiently large lateral displacements that it could be observed to "breathe" under illumination by a stroboscopic lamp. Figure 5 shows a drawing of the deformation observed

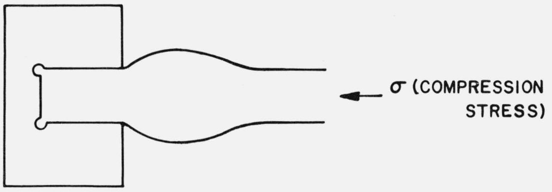

FIGURE 5. *Bulging at contact between grip block and specimen, as observed during fatigue experiments. (Scale exaggerated for purposes of illustration.)*

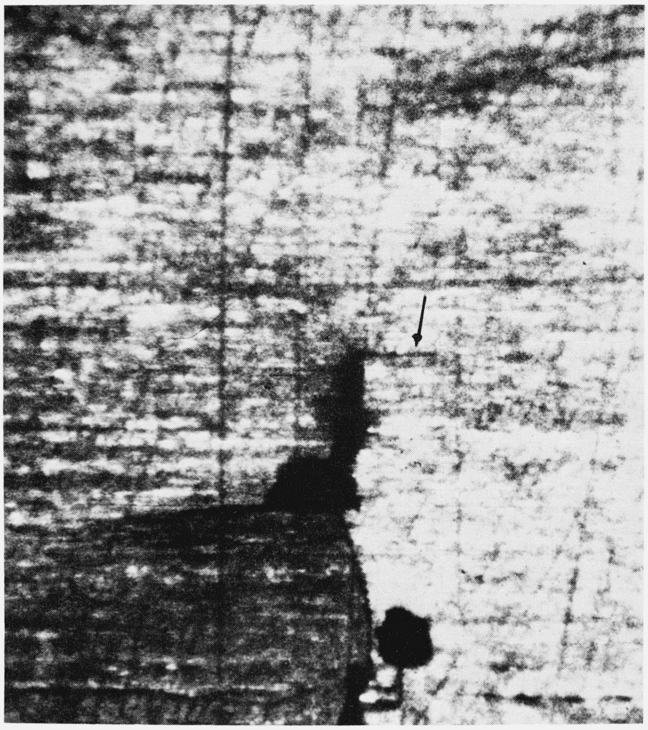

FIGURE 6. *Longitudinal notch extension (arrow) from compressive fatigue crack which underwent complete arrest.*

at the juncture of the specimen and grip block as the specimen was subjected to compression. The bulging of the specimen against the hard surface of the grip evidently served to nucleate the fatigue crack which ultimately caused failure. Bulging of the unnotched graphite fiber specimen probably also occurred, but the deflections of the specimen were too small to observe with the low power microscope used in these experiments.

In another set of experiments [2] it was found that under certain conditions compressive fatigue notches would propagate and then arrest. Figure 6 shows a photograph of a crack which has arrested after propagation. Note that a longitudinal crack has extended from the tip of the main fatigue crack. The authors observed that once longitudinal crack extension occurred at the tip of a transfibrile notch it was extremely difficult to restart fatigue cracking in the transfibrile direction. This suggests a mechanism which may be responsible for the strong coaxing effect observed in the experiments reported above. The authors suggest that at a given stress level there are different rates of fatigue crack nucleation and subsequent crack extension transverse to the fiber direction, and parallel to the fiber direction (i.e., in the matrix). At low stress levels fatigue cracking transverse to the fiber direction may take place very slowly, or might actually cease; since the main mechanism of transfibrile compressive crack extension is micro buckling it would be reasonable to expect that at stress levels below some threshold value no crack nucleation or extension will occur; such thresholds have been observed previously [2]. However, it may still be possible to extend fatigue cracking through the matrix at low stress levels (say, levels below the threshold for transfibrile cracking). In this case, compressive fatigue at low stress levels would result in longitudinal crack extension from the tips of any small notches or flaw sites which might serve as potential nuclei for transfibrile cracking. If the longitudinal cracking is permitted to extend sufficiently far, the entire flaw structure in the material will be changed; all of the flaws which could have served as nuclei of transfibrile cracking will have been converted to T shaped cracks from which only further longitudinal cracking, which is relatively harmless, may proceed. In this case, in order to produce transfibrile fatigue cracking new flaw sites would have to be created, which in most materials takes a long time. The authors propose that different fatigue crack nucleation and extension rates in the fibrile and transfibrile direction is responsible for the coaxing effect shown in figures 2, 3 and 4.

Figure 6 shows a crack tip in a graphite fiber reinforced specimen, which was subjected to tensile fatigue after having first been subjected to compressive fatigue which produced the transfibrile crack [2]. The longitudinal crack extension shown in the figure occurred within the first few cycles of tensile loading; such longitudinal cracking from transfibrile notches under tension is highly typical of unidirectional composites. When the specimen of figure 6 was subjected to compressive fatigue it behaved essentially as an unnotched specimen (longitudinal cracking had obviously removed the main transfibrile notch from the specimen). This observation, and the observations of coaxing of unidirectional composites given above suggest two things which may be of substantial practical importance in structural applications of fiber composites, including composites of more complex configuration. First, if a composite part is to be subjected primarily to compressive loading in service then compressive fatigue by transfibrile cracking should be recognized as one of the most important damage mechanisms which might operate on the part. Second, it would seem to be possible to extend the compressive fatigue life of the part. One way to do this would be to run the part in at low stress level before placing it in service (i.e., to use the coaxing effect of figs. 2, 3, 4). Another way to achieve the same effect would be, where it is possible, to remove the part from service at regular intervals and to subject it to a tensile loading (i.e., to use the "crack removal" phenomenon of fig. 6). Combinations of tensile load excursions and low level fatigue loading might also provide possibilities for extending compressive fatigue life of composite structures.

6. Closure

This report has been based on observations of only a small number of specimens and the data have been taken only on specific coaxing histories (the coaxing curves of figs. 2, 3, 4). While the data here are in no way statistically complete, the phenomenon of coaxing is clear. It is the authors' hope in offering the present note that others may be alerted to the existence of the coaxing phenomenon, and that those to whom the phenomenon may be of value or interest, will undertake their own studies to develop sufficient data to meet their own needs.

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7. References

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